1999

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J Am Acad Audiol 10: 133–150 (1999)

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Abstract

Differences in performance were evaluated between the Widex Senso C8 (omnidirectional) and C9 (directional) hearing aids and analog hearing aids currently worn by 40 subjects with hearing loss. Subjects were fit with the C8 and C9 using the manufacturer's recommended procedure. Differences in performance between the C8 and C9 and the subjects' own hearing aids were assessed using the Speech Perception in Noise (SPIN) test administered at +7, 0, and –7 dB signal-to-noise ratio (SNR) with the noise fixed at 65 and 75 dB SPL. Also, a questionnaire was completed assessing differences in preference between the C9 and the subjects' own hearing aids. The major finding was the presence of a significant advantage of the C9 relative to the C8 and the subjects' own hearing aids at each experimental condition. The magnitude of the advantage provided by the C9 increased as the SNR became more difficult. However, significant differences were not present between the C8 and the subjects' own hearing aids at any experimental condition. The questionnaire revealed a statistically significant preference for the C9 in comparison to the subjects' own hearing aids.

Key Words: Analog, digital, directional, omnidirectional, Senso, signal-to-noise ratio, Speech Perception in Noise

Abbreviations: ANSI = American National Standards Institute, BTE = behind the ear, CIC = completely in the canal, DSP = digital signal processing, FBR = front-to-back ratio, HP = high predictability, ITE = in the ear, LP = low predictability, PI = performance intensity, SNR = signal-to-noise ratio, SPIN = Speech Perception in Noise

Recently, digital signal processing (DSP) was introduced to the hearing health care community for ear-level hearing aids. Theoretically, DSP technology, in comparison to analog signal processing, may provide improved (a) recognition of speech in noise, (b) control of acoustic feedback, (c) compensation for recruitment, and (d) sound quality.

Recently, Widex introduced the Senso hearing aid. The Senso is available in behind-the-ear (BTE), in-the-ear (ITE), and completely-in-the-canal (CIC) models. Among the various BTE models, the C8 (omnidirectional microphone) and C9 (directional microphone) are available. The directional microphone of the C9 has a front-to-back ratio (FBR) of approximately 15 to 20 dB up to 3000 Hz. This is comparable to the 15 to 25 dB FBR reported for a commercially available dual-microphone hearing aid (Bachler and Vonlanthen, 1995). It would be of interest to evaluate the magnitude of signal-to-noise ratio (SNR) improvement offered by this single-microphone system to the dual-microphone system. However, unlike the dual-microphone hearing aid, the C9 cannot be switched between omnidirectional and directional performance. Preves et al (1997), in evaluating a dual-microphone ITE, reported that a majority of subjects preferred having the ability to switch between microphone positions (omnidirectional and directional) because there were situations when each microphone mode outperformed the other. According to these investigators, most subjects preferred the directional mode when listening in

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background noise, but many preferred the omnidirectional mode when listening to speech in quiet. Similar findings have been reported by Frank and Gooden (1973), Nielsen (1973), and Sung et al (1975).

The Senso is a three-channel system. The input signal is divided into three independent frequency channels. The hearing aid can be programmed in situ by use of complex tones to determine the calculated gain and output for each channel. The compression characteristics of the Senso are highlighted by (1) a slow-acting, multiple attack and release time that are fast for signals of short duration and up to 30 seconds for signals whose intensity is fairly stable over time, (2) static compression ratios varying from 1:1 to 3:1 depending upon the magnitude of the residual auditory dynamic range, and (3) a compression threshold as low as 20 dB HPL.

To date, little independent research has been reported evaluating the performance of DSP in comparison to analog hearing aids. This type of information is critical so that hearing health care professionals can accumulate information to make informed decisions concerning which method of signal processing may provide significantly better performance. This information also can be invaluable to manufacturers as they refine DSP technology to provide better performance.

Recently, Valente et al (1998) revealed that significant differences in speech recognition in noise could not be demonstrated between the mean performance of the Senso CX (ITE) and C8 models and the subjects' current hearing aids incorporating analog signal processing. However, on average, subjects preferred the performance of the Senso hearing aids in their daily lives (especially in noise) in comparison to their current analog hearing aids. It is hypothesized that the unique temporal characteristics of the amplifier of the Senso may not have performed to its optimum capability in the way the investigation was designed. That is, the release time of the Senso amplifier is very dependent upon the temporal spectral properties of the incoming signal(s). The release time is relatively short for signals of short duration but unusually long (as long as 30 seconds) for signals that are relatively stable over time. In this study, the duration of the signal(s) (i.e., speech and noise) was typically between 5 to 10 seconds. It is possible that the relatively short duration of the signal and noise did not allow the amplifier of the Senso to provide optimum release from masking.

The primary objectives of the present study were to determine if:

1. Significant differences between the C8, C9, and the subjects' current analog hearing aids were present in the performance on the low-predictability (LP), high-predictability (HP), and/or total Revised Speech Perception in Noise (R-SPIN) scores presented at +7, 0, and −7 dB SNR with continuous noise fixed at 65 and 75 dB SPL and whether any significant differences in performance between the C8 and C9 would result from the addition of the directional microphone present in the C9;
2. Significant subjective differences in preference were present between the C9 and the subjects' current analog hearing aids after using the C9 for 30 days.

PROCEDURES

Subjects

Forty adults with mild to moderately severe bilaterally symmetric sensorineural hearing loss (ANSI, 1989) with no greater than a 15-dB difference in interaural thresholds at 250 to 4000 Hz were evaluated at two sites (20 subjects at Washington University School of Medicine in St. Louis, MO—Site I; 20 subjects at University of California-San Francisco—Site II). The magnitude of hearing loss was within the recommended ranges for the C8 and C9 hearing aids (i.e., no greater than 90 dB HL at 250 Hz to 105 dB HL at 4000 Hz). Figure 1 reports the mean audiogram along with one standard deviation for Site I (upper graph) and Site II (lower graph). Normal middle ear function was assessed via tympanometry using a 220-Hz probe tone. At Site I, the mean age was 71.2 years (SD = 7.2 years), while at Site II the mean age was 66.5 years (SD = 12.9 years). Finally, at Site I, the mean word recognition score for headset presentation was 76.4 percent (SD = 9.6%) and 79.5 percent (SD = 8.9%), while at Site II the mean word recognition score was 83.7 percent (SD = 10.2%) and 81.4 percent (SD = 12.9%) for the right and left ears, respectively.

All subjects had prior experience with binaural amplification for at least 6 months and nearly all expressed satisfaction with their current hearing aids. At Site I the average years of experience with their current hearing aids was 5.3 years (SD = 2.9 years). At Site II, the average years of experience with their current hear-

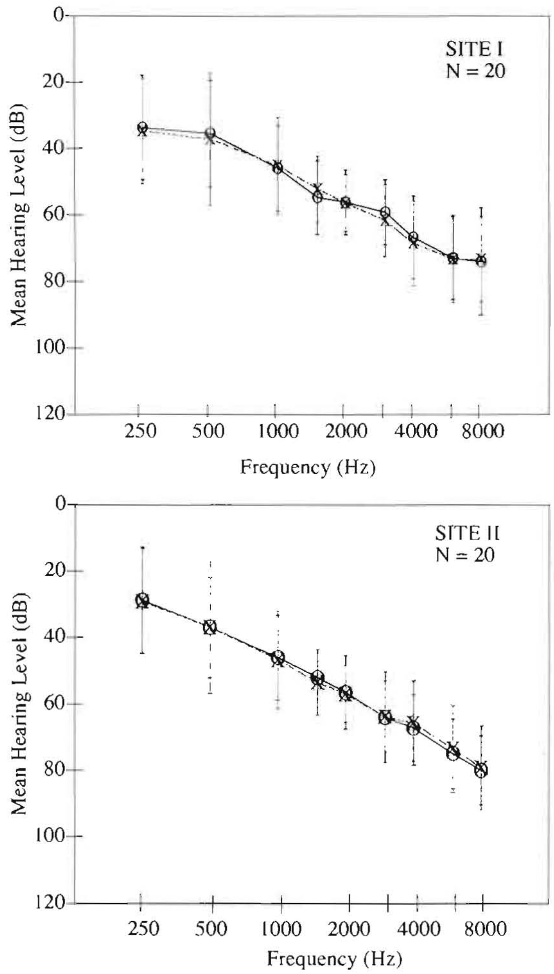

Figure 1 Mean hearing thresholds for Site I (upper) and Site II (lower). Also provided are error bars reporting one standard deviation.

ing aids was 4.3 years (SD = 2.6 years). The second column in Appendices A to C provides information on the signal processing of the subjects' current hearing aids. As can be seen in Appendices A to C, at Site I, seven fittings were two-channel low kneepoint (2B LKP), four fittings were one-channel low kneepoint (1B LKP), one fitting was one-channel high kneepoint (1B HKP), and eight fittings were linear. At Site II, three fittings were two-channel low kneepoint (2B LKP), three fittings were one-channel low kneepoint (1B LKP), one fitting was one-channel high kneepoint (1B HKP), four fittings one-channel with a programmable kneepoint (1B PKP), five fittings were two-channel with a programmable kneepoint (2B PKP), and four fittings were linear.

When recruiting subjects for the present study, the subjects were informed that the purpose of the present study was to evaluate the performance of a new hearing aid. Subjects were not informed about the specific signal processing of the experimental hearing aids. It is important to mention that the majority of subjects used in the present study were recruited from a larger subject research pool and have been involved in a number of projects at both sites. In many of those studies, the subjects did not report objective or subjective advantages for an experimental hearing aid condition. Thus, the experimenters were comfortable that the subjects used in the present study were capable of providing valid responses to the objective and subjective measures used in the current study. Finally, to compensate the subjects for their efforts, subjects were offered the option to purchase the experimental hearing aids at a significantly reduced cost at the conclusion of the study.

Fitting the Senso Hearing Aids

The C8 was always fit first. The manufacturer's recommended protocol was used when fitting this hearing aid. The C8 was coupled to the LP2 portable programmer (software version 3.0) and placed in the ear canal with a custom earmold. Selection of the earmold style, tubing, and venting was based on the magnitude and configuration of the hearing loss. The controls on the LP2 were adjusted to the "Tone (Sensogram)" mode. Using this mode, thresholds were determined in the low, mid, and high channels using the modulated tone signals (duration of approximately 1.5 seconds) generated by the LP2 and presented in situ to the subject through the hearing aid. The initial signal was presented at 10 dB above the predicted threshold (based upon the audiometric results obtained earlier). If there was a response, the signal was decreased in 10-dB steps until there was no response. Then the signal was increased and decreased in 5-dB steps. Threshold was accepted as the lowest level where the subject correctly responded 50 percent of the time.

After threshold was determined in each of the three frequency channels, the controls of the LP2 were changed to perform the "Feedback Test" using the manufacturers' recommended protocol. The Feedback Test is an automatic test consisting of two segments. The first segment determines whether the gain calculated for the three channels based upon the results of the "Sensogram" can be achieved for the magnitude of hearing loss in combination with the earmold used for the fitting. If the required gain can be achieved, "zeros" appear in each of the windows of the three channels. If the calculated gain cannot be achieved, then a negative number appears in any or all windows. The second segment of the feedback test automatically reduces the gain to prevent feedback and the amount of gain reduction is displayed in the three windows.

The presence of a negative feedback value effectively reduces the available gain range for soft input levels by the magnitude of the negative value appearing in the channel and increases the compression kneepoint above 20 dB SPL. For example, if the Sensogram calculated 70 dB of gain for low input levels for the high channel and the feedback value was –5 dB, then the maximum gain for the high channel for soft input levels would be reduced to 65 dB and the kneepoint would increase to approximately 25 dB SPL. Typically, negative feedback values are present if the amount of calculated gain range cannot be achieved because of circumstances associated with the earmold (i.e., venting; openings between the earmold and ear canal wall).

In the mid channel at Site I, two ears (5%) had feedback values ranging from –6 to –8 dB, while at Site II, nine ears (22.5%) had feedback values ranging from –4 to –11 dB. In the high channel at Site I, 32 ears (80%) had feedback values ranging from –6 to –18 dB, while at Site II, 31 ears (77.5%) had feedback values ranging from –3 to –21 dB.

After the C8 was programmed binaurally, the R-SPIN test was administered on the same day at the six experimental conditions (–7, 0, and +7 dB SNR with the input noise levels at 65 and 75 dB SPL). Testing time was approximately 1.5 hours. After completing the R-SPIN, the C9 hearing aids were adjusted on the same day using the same parameters (gain, output, and feedback levels) programmed for the C8. The subjects wore the C9s for 4 weeks and returned to the respective sites where the R-SPIN was readministered at the same six experimental conditions.

Revised Speech Perception in Noise

The eight lists of the R-SPIN were distributed by Cosmos Distributing Inc. and recorded on a compact disc (CD). Each list contains 50 sentences for which the subject's task is to identify the final word of each sentence. One half of the sentences are LP items, which supply no contextual cues to identify the final word, while the other half are HP items, which have contextual cues. The R-SPIN has been described in great detail (Kalikow et al, 1977; Bilger et al, 1984). The scores for the LP and HP items are then summed to obtain the total R-SPIN score. The total R-SPIN score can also be obtained by using a nomograph supplied with the R-SPIN. Using the nomograph, the investigators found the column corresponding to the LP item score and the row corresponding to the HP item score. Where the row and column intersect was the resulting total R-SPIN "percent hearing for speech" score. Separate analysis of variance (ANOVA) of the total R-SPIN score using both methods revealed no differences; therefore, the summed method is used in this paper when reporting the total R-SPIN score.

For this study, the sentences of the R-SPIN were presented at +7 dB, 0 dB, and –7 dB SNR while the noise level was fixed at 65 dB and 75 dB SPL. Instead of using the 12-talker babble accompanying the R-SPIN, a custom CD containing 39 minutes of party noise was prepared. For this study, the party noise was played for at least 30 seconds before the first sentence from the R-SPIN was introduced to the subject. In addition, the party noise was continuously on during the course of completing each R-SPIN list. The party noise was recorded in the former Copenhagen Stock Exchange, which has physical dimensions of approximately 40 meters (length) by 30 meters (width) by 7 meters (height) and a reverberation time of approximately 4 to 5 seconds when unoccupied. The recording was made during a dinner party with the room filled with over 300 guests with piano music in the background. A Bruel and Kjaer sound level meter, equipped with a ½-inch freefield condenser microphone (#4188), was used to transduce the acoustic input into electrical form and recorded on a Sony digital audiotape (DAT) recorder. Later, the recording was examined and the longest, uninterrupted passage with no recognizable speech and no abrupt change in overall level was selected. This 1-minute, 6-second segment was looped and overlap-added in an editing process to result in the final 39 minutes of party noise and re-recorded on a CD. Figure 2 reveals the spectrum of the party noise. The purpose for using this noise rather than the noise provided by the R-SPIN recording was that the noise was on continuously. Finally, all treatment levels of the independent variables SNR (–7 dB, 0 dB, and +7 dB) and noise level (65 dB SPL and 75 dB SPL) were counterbalanced to control for order effects. The R-SPIN scores were measured on the subjects' own aids when they entered the study. R-SPIN scores

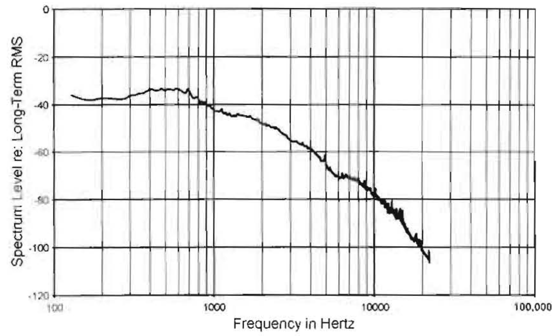

Figure 2 Spectrum level (dB SPL) of the continuous noise used in this study.

were measured for the C8 on the second visit and R-SPIN scores were measured for the C9 after the subjects wore these hearing aids for 4 weeks.

R-SPIN scores were obtained for the LP-item, HP-item, and total R-SPIN conditions. The range for the LP-item and HP-item scores can be from 0 to 25, in steps of 1 where 0 means the subject did not record any of the items correctly and 25 means the subject recorded all of the items correctly.

To ensure that the signal and noise levels were correct, a 1-inch microphone connected to a Quest 215 sound level meter and OB-45 octave filter was placed at ear level (114.3 cm from the floor) 1.1 meters from a loudspeaker at 0° or 180° azimuth with the head absent. The attenuator and VU meter of the audiometer was adjusted for channel 1 until the required overall levels (58, 65, and 72 dB SPL for the 65 dB SPL condition and 68, 75, and 82 dB SPL for the 75 dB SPL condition) were obtained using the 1000-Hz calibration tone. A similar procedure was used on channel 2 to calibrate the overall levels of the party noise (65 and 75 dB SPL) to create the +7 dB, 0 dB, and –7 dB SNR conditions. The R-SPIN and party noise stimuli were presented from two independent CDs and fed into channels 1 and 2 of the audiometer. LP item, HP item, and total R-SPIN scores were obtained for the three SNR conditions, two noise levels (65 and 75 dB SPL), and for three aided conditions (current, C8 and C9 hearing aids).

In this study, the sentences were presented at 0° azimuth and the party noise presented at 180° azimuth. The subject was seated approximately 1.1 meters equidistant from two loudspeakers in a 2.58 × 2.74 m (Site I) and 2.2 × 2.2 m (Site II) double-walled sound suite. Neither sound suite was anechoic and reverberation time was not measured. However, Studebaker et al (1980) and Madison and Hawkins (1983) reported reverberation times of 0.1 to 0.6 seconds in sound suites of similar size.

Subjective Assessment

Subjects were asked to complete a 24-item questionnaire (Table 1) assessing preferences between the C9 and their current hearing aids after wearing the C9 for 30 days. Items included sound quality, loudness, and overall performance in a variety of listening situations. The final item in the questionnaire reported the overall preference between the C9 and their current hearing aids. For each question, the subject was asked to assess if the C9 or their current hearing aids provided better performance (column 1 or 2), equivalent performance (column 3), or if neither hearing aid provided satisfactory performance (column 4).

RESULTS AND DISCUSSION

R-SPIN

R-SPIN scores were arcsine-transformed prior to statistical analysis to normalize the variance (Studebaker, 1985). Figures 3 to 5 report the mean item scores for the LP (see Fig. 3), HP (see Fig. 4), and total R-SPIN (see Fig. 5) scores for Site I (upper graph) and Site II (lower graph) for the subject's current aid, C8, C9, at the six listening conditions. These data also appear in Table 2, along with the standard deviation and the mean difference in performance between sites for the three hearing aid conditions and six presentation levels. Finally, the individual measures of the LP, HP, and total R-SPIN scores, for the three SNR and two noise level conditions, are provided for the own aid (Appendix A), C8 (Appendix B), and C9 (Appendix C) hearing aid conditions.

The LP, HP, and total R-SPIN scores data were analyzed (SAS, 1989) using a four-way split-plot ANOVA with repeated measures for the three within-subject factors (hearing aids, SNR, noise level) and one between-subject factor (site) (Kirk, 1982).

LP Item Score

First, the ANOVA revealed a significant two-factor SNR by hearing aid ($F = 12.81$, $df = 4, 35$, $p < .001$) interaction (see Fig. 3). Post hoc analysis using the Tukey honestly significant difference (HSD) test revealed that the mean score for the C9 (20.4, 16.6, 11.1 items) was signifi-

Table 1 Questionnaire Used to Determine Preference between the Subjects' Current Hearing Aids and the Senso (Experimental Hearing Aids)

Speech Quality	*Current Hearing Aids*	*Experimental Hearing Aids*	*Both*	*Neither*
Speech was more:				
Distinct				
Pleasant				
Natural				
Comfortably loud				
Uncomfortably loud				
Performance was better with a close friend one on one				
Performance was better with a stranger one on one				
Performance was better listening to a speaker across the room				
Performance was better listening to TV with no one else talking				
Performance was better listening to TV with one or more people talking in the background				
Performance was less frustrating				
Performance was better listening at a meeting with one speaker				
Performance was better listening at a meeting with several speakers				
Performance was better listening at a family gathering				
Performance was better listening to the radio in the car				
Performance was better listening to a passenger in the car				
Performance was better listening in an "elegant" restaurant				
Performance was better listening in a family restaurant				
Performance was better listening to sounds at a distance				
Performance was better listening in a house of worship				
Performance was better listening in a movie theater				
Performance was better listening to recorded music				
Quiet sounds were more audible				
My performance was best with				

cantly better (p < .01) than the mean score for the C8 (17.2, 10.6, 4.3 items) and the subjects' own hearing aids (16.3, 9.6, 3.7 items) at +7, 0, and −7 dB SNR, respectively. No significant differences were found in the mean scores between the C8 (17.2, 10.6, 4.3 items) and the subjects' own hearing aids (16.3, 9.6, 3.7 items) at any SNR condition. Second, there was a significant SNR by site (F = 17.92, df = 2, 37, p < .0001) interaction. The Tukey HSD revealed that the mean scores for Site I (8.2 items) was significantly better (p < .01) than the mean score at Site II (4.6 items) at −7 dB SNR. No significant differences were found in mean scores between Site I (13.5, 17.9 items) and Site II (11.1, 17.9 items) at 0 and +7 dB SNR, respectively. Third, there was a significant main effect for hearing aids (F = 56.51, df = 2, 37, p < .0001). The Tukey HSD revealed that the overall (i.e., across SNR, levels and sites) mean performance for the C9 (16.0 items) was significantly better (p < .01) than the overall mean performance of the C8 (10.7) and the subjects' own aids (9.9 items). However, significant differences were not present in mean

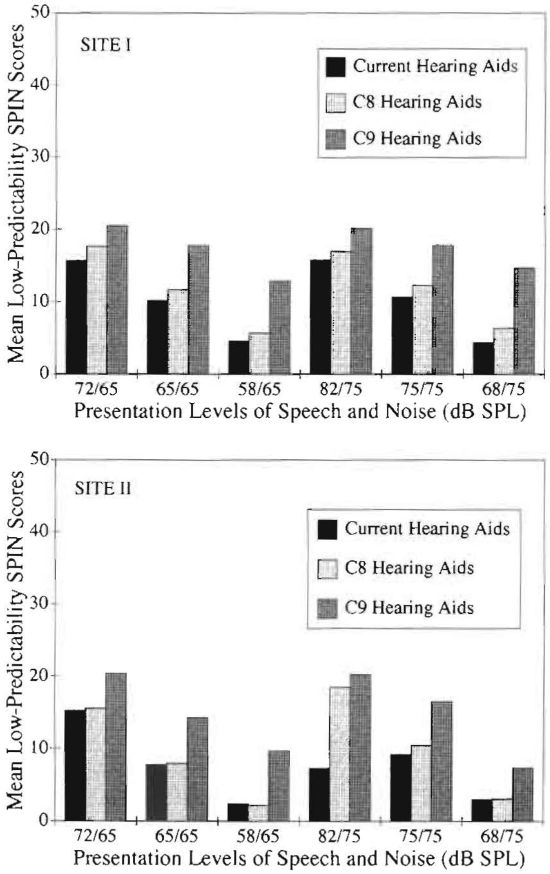

Figure 3 Mean low-predictability SPIN scores for the Senso C8 and C9 and current hearing aids at +7, 0, and –7 dB SNR with the noise level fixed at 65 and 75 dB SPL for Site I (upper) and Site II (lower).

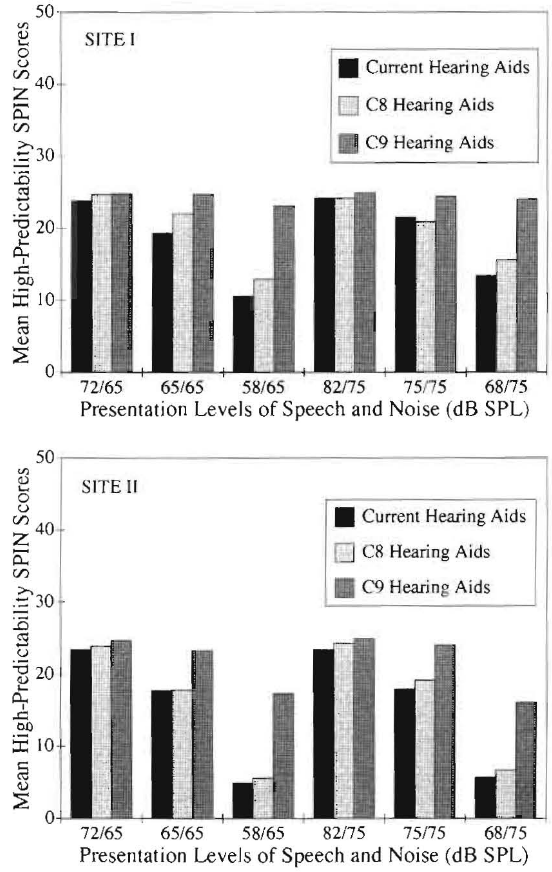

Figure 4 Mean high-predictability SPIN scores for the Senso C8 and C9 and current hearing aids at +7, 0, and –7 dB SNR with the noise level fixed at 65 and 75 dB SPL for Site I (upper) and Site II (lower).

scores between the C8 (10.7 items) and the subjects' own aids (9.9 items). Finally, there was a significant SNR effect ($F = 676.65$, $df = 2, 37$, $p < .0001$). The Tukey HSD revealed that the overall (i.e., across hearing aids, overall level and sites) mean performance for +7 dB (17.9 items) was significantly better ($p < .01$) than the mean performance at 0 dB (12.3 items) and –7 dB (6.4 items). In addition, the mean performance at 0 dB (12.3 items) was significantly better than the mean performance at –7 dB (6.4 items).

HP Item Score

First, the ANOVA revealed a significant two-factor SNR by hearing aid ($F = 52.71$, $df = 4, 35$, $p < .0001$) interaction (see Fig. 4). Post hoc analysis using the Tukey HSD revealed that the mean score for the C9 (20.1 items) was significantly better ($p < .01$) than the mean score for the C8 (10.2 items) and the subjects' own hearing aids (8.9 items) at –7 dB SNR. No significant differences were found in the mean scores between the C9 (24.1, 24.8 items), C8 (19.9, 24.3 items), and the subjects' own hearing aids (19.2, 23.7 items) at 0 and +7 dB SNR, respectively. Second, there was a significant SNR by site ($F = 21.81$, $df = 2, 37$, $p < .0001$) interaction. The Tukey HSD revealed that the mean scores for Site I (16.7 items) was significantly better ($p < .01$) than the mean score at Site II (9.4) at –7 dB SNR. No significant differences were found in mean scores between Site I (22.2, 24.5 items) and Site II (20.0, 24.1 items) at 0 and +7 dB SNR, respectively. Third, there was a significant main effect for hearing aids ($F = 82.93$, $df = 2, 37$, $p < .0001$). The Tukey HSD revealed that the overall (i.e., across SNR, levels and sites) mean performance for the C9 (23.0 items) was significantly better ($p < .01$) than the overall mean performance of the C8 (18.1) and the subjects' own aids (17.3 items). However, there

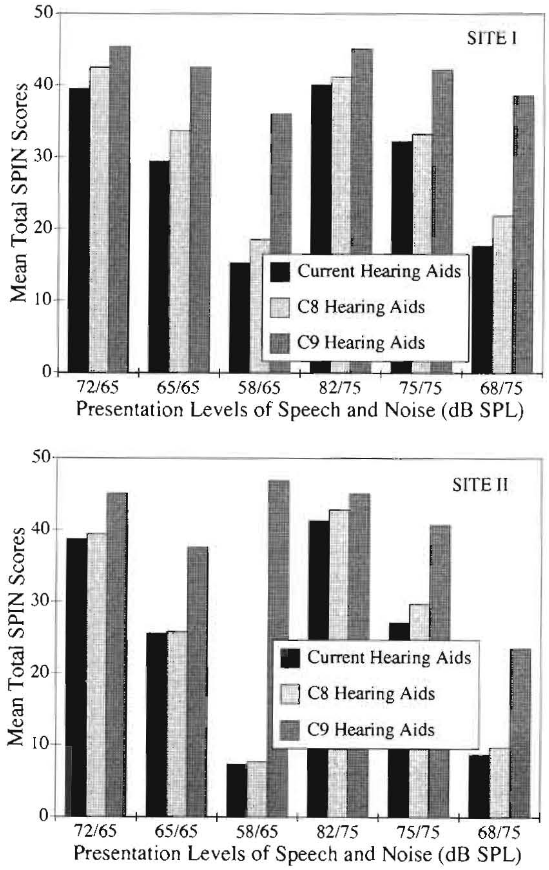

Figure 5 Mean total SPIN scores for the Senso C8 and C9 and current hearing aids at +7, 0, and – 7dB SNR with the noise level fixed at 65 and 75 dB SPL for Site I (upper) and Site II (lower).

were no significant differences in scores between the C8 and the subjects' own aids. Fourth, there was a significant SNR effect (F = 222.29, df = 2, 37, p < .0001). The Tukey HSD revealed that the overall (i.e., across hearing aids, overall level and sites) mean performance for +7 dB (24.3 items) was significantly better (p < .01) than the mean performance at 0 dB (21.1 items) and –7 dB (13.0 items). In addition, the mean performance at 0 dB (21.1 items) was significantly better than the mean performance at –7 dB (13.0 items). Finally, there was a significant site effect (F = 15.04, df = 1, 38, p < .001) where the overall (across hearing aids, overall level and SNR) mean performance for Site I (21.1 items) was significantly better than the mean performance for Site II (17.8 items).

Total R-SPIN Score

First, the ANOVA revealed a significant two-factor SNR by hearing aid (F = 48.81, df = 4, 35, p < .0001) interaction (see Fig. 5). Post hoc analysis using the Tukey HSD test revealed that the mean score for the C9 (31.2, 40.7 items) was significantly better (p < .01) than the mean score for the C8 (14.5, 30.6 items) and the subjects' own hearing aids (12.6, 28.8 items) at –7 dB and 0 dB SNR. No significant differences were found in the mean scores between the C9 (45.2 items), C8 (41.5 items), and the subjects' own hearing aids (40.2) at +7 dB SNR. Second, there was a significant SNR by site (F = 29.28, df = 2, 37, p < .0001) interaction. The Tukey HSD revealed that the mean score for Site I (24.9 items) was significantly better (p < .01) than the mean score at Site II (13.9 items) at –7 dB SNR. No significant differences were found in mean scores between Site I (35.7, 42.4 items) and Site II (31.0, 42.0 items) at 0 and +7 dB SNR, respectively. Third, there was a significant main effect for hearing aids (F = 129.64, df = 2, 37, p < .0001). The Tukey HSD revealed that the overall (i.e., across SNR, levels and sites) mean performance for the C9 (39.0 items) was significantly better (p < .01) than the overall mean performance of the C8 (28.8 items) and the subjects' own aids (27.2 items), but there were no significant differences in scores between the C8 and the subjects' own aids. Fourth, there was a significant SNR effect (F = 539.88.29, df = 2, 37, p < .0001). The Tukey HSD revealed that the overall (i.e., across hearing aids, overall level and sites) mean performance for +7 dB (42.2 items) was significantly better (p < .01) than the mean performance at 0 dB (33.4 items) and –7 dB (19.4 items). In addition, the mean performance at 0 dB (33.4 items) was significantly better (p < .01) than the mean performance at –7 dB (19.4 items). Finally, there was a significant site effect (F = 8.01, df = 1, 38, p < .01) where the overall (across hearing aids, overall level and SNR) mean performance for Site I (34.3 items) was significantly better than the mean performance for Site II (29.0 items).

Questionnaire on Preference between Hearing Aids

Tables 3 and 4 report the responses to the 24 items relating to sound quality (#1–3), loudness (#4–5), listening situations (#6–23), and overall performance (#24). Table 3 reports the responses for the subjects from Site I, while Table 4 reports the responses for the subjects from Site II. The number in each row by column combination in Tables 3 and 4 represents the number of subjects responding to each question.

Table 2 Means and Standard Deviations for the Low-Predictability, High-Predictability, and Total SPIN Scores for Sites I and II for the Three Hearing Aid Conditions and Six Presentation Levels

	72/65			*65/65*			*58/65*			*82/75*			*75/75*			*68/75*		
	Own	*C8*	*C9*	*Own*	*C8*	*C9*	*Own*	*C8*	*C9*	*Own*	*C8*	*C9*	*Own*	*C8*	*C9*	*Own*	*C8*	*C9*
Low Predictability																		
Site I																		
SD	15.7	17.7	20.6	10.2	11.7	17.8	4.6	5.7	12.9	15.8	17.0	20.2	10.7	12.3	17.8	4.4	6.4	14.7
Mean	(5.3)	(3.1)	(2.6)	(6.8)	(4.7)	(3.2)	(4.6)	(3.9)	(4.5)	(4.9)	(3.8)	(2.5)	(5.1)	(6.7)	(2.6)	(4.3)	(5.2)	(4.1)
Site II																		
Mean	15.3	15.6	20.4	7.8	8.0	14.3	2.4	2.2	9.7	18.0	18.5	20.3	9.2	10.5	16.6	3.0	3.1	7.4
SD	(4.8)	(4.6)	(2.8)	(5.5)	(4.0)	(4.6)	(3.9)	(2.2)	(5.5)	(3.9)	(3.9)	(2.9)	(6.1)	(4.8)	(4.6)	(3.2)	(2.5)	(4.4)
Difference	0.4	2.1	0.2	2.4	3.7	3.5	2.3	3.5	3.3	–2.2	–1.5	–0.1	1.5	1.8	1.2	1.4	3.3	7.3
High Predictability																		
Site I																		
Mean	23.8	24.7	24.8	19.3	22.0	24.7	10.6	12.9	23.1	24.2	24.2	24.9	21.5	20.9	24.4	13.4	15.6	24.0
SD	(2.2)	(0.7)	(0.5)	(7.3)	(3.7)	(0.5)	(7.4)	(7.2)	(2.1)	(1.3)	(1.4)	(0.3)	(3.5)	(5.7)	(1.0)	(8.5)	(6.6)	(1.8)
Site II																		
Mean	23.4	23.9	24.7	17.7	17.8	23.3	4.9	5.6	17.3	23.4	24.3	24.9	17.9	19.2	24.1	5.7	6.7	16.1
SD	(1.6)	(1.3)	(0.8)	(7.0)	(5.4)	(2.6)	(6.7)	(5.0)	(5.1)	(2.1)	(0.9)	(0.4)	(7.3)	(4.2)	(0.9)	(6.5)	(5.3)	(5.2)
Difference	0.4	0.8	0.1	1.6	4.2	1.4	5.7	7.4	5.8	0.8	–0.1	0.0	3.6	1.7	0.3	7.7	8.9	7.9
Total																		
Site I																		
Mean	39.5	42.5	45.4	29.4	33.7	42.5	15.3	18.6	36.0	40.1	41.2	45.1	32.2	33.2	42.2	17.7	21.9	38.6
SD	(6.9)	(3.1)	(2.8)	(13.2)	(7.9)	(3.4)	(11.3)	(10.6)	(6.2)	(5.3)	(4.8)	(2.6)	(8.1)	(11.5)	(2.7)	(12.1)	(11.0)	(5.2)
Site II																		
Mean	38.7	39.4	45.1	25.5	25.8	37.6	7.3	7.7	26.9	41.3	42.8	45.1	27.1	29.7	40.7	8.7	9.7	23.5
SD	(6.1)	(5.2)	(3.2)	(11.8)	(8.8)	(6.5)	(10.5)	(7.1)	(9.8)	(5.5)	(4.1)	(2.8)	(12.6)	(8.6)	(4.9)	(9.4)	(7.2)	(9.0)
Difference	0.8	3.1	0.2	3.9	7.9	4.9	8.1	10.9	9.1	–1.2	–1.6	0	5.1	3.5	1.5	9.0	12.2	15.1

Separate McNemar χ^2 tests (SAS, 1989) were performed on the data appearing in Tables 3 and 4. The McNemar χ^2 test is used to determine if significant differences are present between related measures on the same subject. For Site I (see Table 3), the results of the McNemar χ^2 test revealed that a significantly ($p < .001$) greater number of subjects preferred the C9 to their current aids for all items with the exception of item 13 ("performance was better listening at a meeting with several speakers"). Finally, there were no significant differences between the C9 and subjects' own hearing aids in the perception that either one provided an amplified sound that was uncomfortably loud (item 5).

For Site II (see Table 4), the results of the McNemar χ^2 test revealed that a significantly greater number of subjects ($p < .001$) preferred the C9 to their current aids for all items ($p < .01$). Finally, there were no significant differences between the C9 and subjects' own hearing aids in the perception that either one provided an amplified sound that was uncomfortably loud (item 5).

DISCUSSION

C8 versus Own Hearing Aids

As stated in the introduction, Valente et al (1998) could not demonstrate significant differences in performance between the C8 and CX and the subject's current analog hearing aids. One reason suggested by Valente et al (1998) for the inability of the Senso hearing aids to perform significantly better than the subjects' current hearing aids was a possible error in the experimental methodology. That is, the signal and noise were presented for less than 30 seconds and this duration may not have allowed the signal processing of the Senso to provide maximum amplification. In the current study, the background noise was continuous. However, once again, significant differences could not be demonstrated between the C8 and subjects' current hearing aids. This suggests that presenting noise for short or long durations does not significantly impact the performance of the Senso C8 on this type of speech recognition test when compared to the performance of hearing aids

Table 3 Responses to the Preference Questionnaire at Site I

Speech Quality	*Current Hearing Aids*	*Experimental Hearing Aids*	*Both*	*Neither*	*No Response*
Speech was more					
Distinct	1	15	4	0	0
Pleasant	1	13	5	0	1
Natural	2	12	4	2	0
Comfortably loud	2	10	5	1	2
Uncomfortably loud	3	2	0	13	2
Performance was better with a close friend one on one	2	10	8	0	0
Performance was better with a stranger one on one	1	11	8	0	0
Performance was better listening to a speaker across the room	2	13	2	3	0
Performance was better listening to TV with no one else talking	0	11	8	0	1
Performance was better listening to TV with one or more people talking in the background	2	12	1	5	0
Performance was less frustrating	2	14	2	1	1
Performance was better listening at a meeting with one speaker	2	12	3	1	2
Performance was better listening at a meeting with several speakers	2	9	2	5	2
Performance was better listening at a family gathering	2	13	4	1	0
Performance was better listening to the radio in the car	1	13	5	0	1
Performance was better listening to a passenger in the car	1	13	5	1	0
Performance was better listening in an "elegant" restaurant	1	14	5	0	0
Performance was better listening in a family restaurant	2	13	3	1	1
Performance was better listening to sounds at a distance	4	11	2	3	0
Performance was better listening in a house of worship	2	12	1	2	3
Performance was better listening in a movie theater	2	10	2	1	5
Performance was better listening to recorded music	1	12	7	0	0
Quiet sounds were more audible	4	13	2	1	0
My performance was best with	3	17	0	0	0
Total	45	285	88	41	21

Each column represents the number of subjects responding to each of the four choices and the number of subjects who did not respond to that question. Each row represents the total responses of the 20 subjects.

incorporating analog signal processing. Researchers need to continue to investigate new ways to evaluate the performance of hearing aids incorporating DSP. As reported earlier, a recent study reported subjective preferences for the hearing aids with DSP that could not be demonstrated in the laboratory (Valente et al, 1998). Clinically, the authors of the present study have fit numerous patients who report significantly greater satisfaction with hearing aids incorporating DSP in comparison to their previous hearing aids using analog signal processing. When patients with previous hearing aid experience decide to purchase DSP technology, they typically report improved recognition of speech in noisy environments and greater listening comfort compared to their current hearing aids. A reason why DSP has not been shown to be significantly better than analog signal processing in the laboratory, but significantly better in subjective preferences, is that the full dynamic range of speech available in "real life"

Table 4 Responses to the Preference Questionnaire at Site II

Speech Quality	*Current Hearing Aids*	*Experimental Hearing Aids*	*Both*	*Neither*	*No Response*
Speech was more					
Distinct	1	13	3	2	1
Pleasant	1	8	5	2	4
Natural	1	9	5	2	3
Comfortably loud	2	10	2	3	3
Uncomfortably loud	4	2	2	8	4
Performance was better with a close friend one on one	2	10	4	3	1
Performance was better with a stranger one on one	2	11	2	4	1
Performance was better listening to a speaker across the room	2	14	1	3	0
Performance was better listening to TV with no one else talking	3	14	2	1	0
Performance was better listening to TV with one or more people talking in the background	4	11	1	2	2
Performance was less frustrating	2	14	0	4	0
Performance was better listening at a meeting with one speaker	4	12	3	1	0
Performance was better listening at a meeting with several speakers	3	9	1	3	4
Performance was better listening at a family gathering	2	15	1	2	0
Performance was better listening to the radio in the car	3	10	3	3	1
Performance was better listening to a passenger in the car	4	13	0	3	0
Performance was better listening in an "elegant" restaurant	4	11	2	1	2
Performance was better listening in a family restaurant	4	12	1	3	0
Performance was better listening to sounds at a distance	3	10	1	5	1
Performance was better listening in a house of worship	2	8	0	3	7
Performance was better listening in a movie theater	3	7	0	2	8
Performance was better listening to recorded music	5	10	0	3	2
Quiet sounds were more audible	3	12	0	3	2
My performance was best with	3	12	1	3	1
Total	67	257	40	69	47

Each column represents the number of subjects responding to each of the four choices and the number of subjects who did not respond to that question. Each row represents the total responses of the 20 subjects.

is probably not represented on the recording of the speech material used in the current experiment. Also, another possible explanation for the lack of agreement between objective and subjective measures is that room acoustics are controlled in the laboratory but not in the "real world." Perhaps the manner in which current research is being employed to assess DSP performance is not assessing the full potential DSP may have in providing significant improvement when listening in noise and providing greater listener comfort. On the other hand, it is possible that no matter how the experimental design is manipulated, significant differences between DSP and analog signal processing may not be consistently demonstrated.

As pointed out, one of the major findings was that significant differences were not found in performance between the C8 and the subjects' current aids. However, it must be pointed out that the performance of the C8 was assessed at the time of the fit, whereas the performance of the

C9 was completed after the subject wore the hearing aids for 4 weeks. In addition, as noted earlier, the subjects wore their current hearing aids for an average of 4.3 to 5.3 years at Sites I and II, respectively. Cox and Alexander (1992), Gatehouse (1989, 1992, 1993), and Horwitz and Turner (1997) reported improved aid benefit (i.e., acclimatization) over the first few months of use. That is, performance improves as the ear becomes acclimatized to the speech signal it is accustomed to hearing. However, some reports (Bentler et al, 1993; Saunders and Cienkowski, 1997) could not demonstrate the acclimatization effect. Therefore, it is possible that greater differences in performance between the C8 and the subjects' current hearing aids might have emerged if differences in performance were measured after the subjects had worn the C8 hearing aids for at least 4 weeks.

C9 versus C8 and Own Aids

Another major finding was the significant release from background noise provided by the C9 relative to the C8 and the subjects' current hearing aids. It is difficult to reason that the benefit provided by the C9 was exclusively related to DSP because the C8 and C9 were programmed equally and differences in performance were not found between the C8 and the subjects' current hearing aids. Part of the improvement in the performance of the C9 (relative to the C8) may be related to acclimatization as described earlier (i.e., subject wore the C9 for 4 weeks while performance was evaluated immediately upon fitting the C8). However, clearly, the major factor for the improvement provided by the C9 is the directional microphone. Figure 6 illustrates the FBR of the directional microphone of the C9. Signals from the rear are attenuated by 15 to 20 dB to 3000 Hz. This is significantly greater than the 8 to 13 dB FBR at 500 to 3000 Hz for a directional microphone by Madison and Hawkins (1983). Numerous studies (Lentz, 1972; Frank and Gooden, 1973; Nielsen, 1973; Mueller and Johnson, 1979; Hawkins and Yacullo, 1984; Leeuw and Dreschler, 1991) have revealed that a single directional microphone can provide a mean SNR improvement of 3 to 4 dB. Mueller and Johnson (1979) reported improved speech recognition in noise for the Synthetic Sentence Identification test as the FBR reported at 1000 Hz increased from 6 to 20 dB. In addition, several studies revealed that the directional advantage increased as the listening situation became progressively more difficult (i.e., little or no

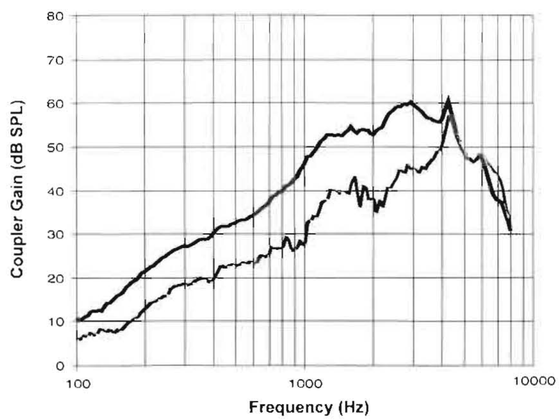

Figure 6 Front-to-back response of the C9 measured on KEMAR.

advantage at positive SNRs, but increased advantage at more negative SNRs) (Lentz, 1972; Frank and Gooden, 1973; Mueller and Johnson, 1979).

However, the FBR reported in Figure 6 is somewhat less than the 15 to 25 dB FBR reported by Valente et al (1995) for a dual-microphone hearing aid that provided a mean SNR improvement of 7.4 to 7.8 dB. Additional studies on dual microphones have revealed mean improvement in SNR between 4.2 to 7.8 dB for BTE designs (Lurquin and Rafhay, 1996; Gravel et al, 1998) and 2 to 3 dB for ITE designs (Preves et al, 1997) using a variety of speech signals that did not include the R-SPIN. Therefore, it is difficult to conclude that the magnitude of improvement seen in this investigation for the C9 at the –7 dB SNR for the total R-SPIN scores can be explained by the improved FBR provided by the single directional microphone incorporated in the C9. However, it is possible that the speech enhancement algorithm used in the Senso may work in synergy with the directional microphone to enhance speech recognition in noise to a degree greater than has been reported in the past when the directional microphone (single or dual) was coupled to analog signal processing. This is an area requiring additional investigation.

To illustrate the improvement in SNR provided by the C9, Figure 7 converts the data reported in Figure 5 (total R-SPIN) into performance-intensity (PI) functions for the C9, C8, and subjects' own aids. That is, the total R-SPIN score was collapsed across the two sites for both noise conditions (i.e., 65 and 75 dB SPL) and multiplied by 2 percent to arrive at the total R-SPIN score in percent. The data

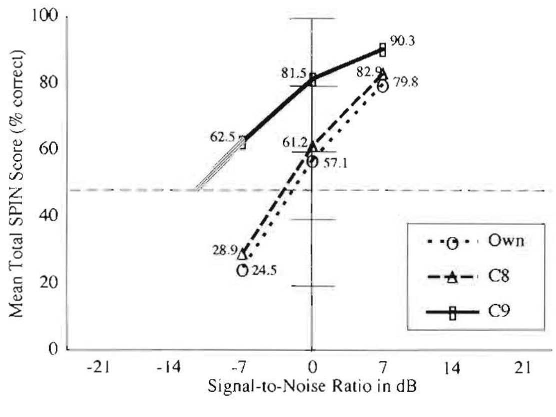

Figure 7 Mean performance-intensity (PI) functions for the total R-SPIN scores for the C9, C8, and subjects' own hearing aids at + 7, 0, and –7 dB SNR collapsed across sites.

points in Figure 7 report the mean R-SPIN score for each of the three SNR and the three hearing aids. The dashed vertical line represents the 50 percent score. Therefore, to determine the SNR for each hearing aid at the three SNR conditions, one can determine where the PI line intersects with the 50 percent vertical line. In doing this, the 50 percent performance for the subjects' own hearing aids occurred at approximately –3 dB SNR, while the 50 percent performance for the C8 was at a SNR of approximately –5 dB. This represents an improvement of 2 dB provided by the C8 relative to the subject's own hearing aid. The poorest performance provided by the C9 was 62.5 percent at –7 dB SNR. Therefore, the PI function (shaded area) was extended in a linear fashion to intersect the 50 percent line. Using this method, the PI line for the C9 intersects the 50 percent line at approximately –12 dB. This suggests that the C9 provided 7-dB improvement in the SNR relative to the performance of the C8 and 9 dB relative to the performance of the subjects' own hearing aids. A word of caution should be emphasized at this point. That is, Figure 7 assumes that the PI function will decrease in a linear fashion beyond the –7 dB SNR. It is unlikely that the performance of the subjects would have decreased in such a linear fashion in view of the fact that performance decreased in less than a linear fashion between the 0- and –7-dB points. Thus, it is possible that the "true" advantage provided by the C9 over the C8 and the subjects' own hearing aids under the more difficult listening situations was probably less than 7 to 9 dB cited above.

Differences between Sites

The results between sites were not significantly different from each other for most of the experimental conditions. However, statistically significant differences were present between sites for LP, HP, and total scores at –7 dB SNR. These differences ranged from 5.7 for the HP items for the own aid condition with the noise at 65 dB SPL to 15.2 for the total score for the C9 with the noise at 75 dB SPL (see Table 2). Looking at Figure 1, the average hearing loss at Site I was better by 4 dB to 6 dB at 250 to 1000 Hz, respectively. This better hearing at 250 to 1000 Hz at Site I in combination with the amplification and the low kneepoint (20 dB SPL) of the Senso may have allowed more of the speech signal to be audible than was possible for the subjects at Site II. Improved audibility becomes more important as the listening situation becomes increasingly more difficult.

A second explanation for the observed differences between sites at the –7 dB SNR may be related to differences in the feedback values present in the mid and high channel. As mentioned earlier, in the mid channel, two ears at Site I (5%) had feedback values ranging from –6 to –8 dB, while at Site II nine ears (22.5%) had feedback values ranging from –4 to –11 dB. Thus, when listening through the Senso hearing aids, more subjects at Site II had less available gain and a higher compression kneepoint in the mid and high channels than the subjects at Site I. These two factors combine and interact to provide these subjects with less gain for soft speech than for those subjects where the feedback values in the mid channel were 0 dB. Again, the effect of this on speech recognition becomes more problematic as the listening situation becomes more difficult. Also, in the high channel, 32 ears at Site I (80%) had feedback values ranging from –6 to –18 dB, while 31 ears at Site II had feedback values ranging from –3 to –21 dB. Although the number of ears with negative feedback values were similar between sites, the magnitude of the negative values were somewhat greater at Site II. Again, it is hypothesized that the presence of slightly greater negative feedback values may have reduced the available gain in the high channel for soft speech for more subjects at Site II than occurred for the subjects at Site I.

A final possible reason for the observed difference between Sites I and II may be related to slight differences in calibration of the sound field. For calibration, the CDs in this study provided a 1000-Hz calibration tone. Due to standing waves caused by a 1000-Hz continuous tone, it is possible that slight differences in calibrated levels may have occurred between the two sites. In addition, the effect of these possible differences may only become apparent as the listening situation became more difficult. That is, at higher SNRs, differences in subject performance due to calibration differences may not appear because of the redundancy of the signal. However, as the listening situation becomes more difficult, the assistance provided by the redundancy of the signal diminishes and differences in performance may emerge. This potential artifact has been eliminated by a new version of the CD by including a 1000-Hz modulated tone as the calibrating signal. Unfortunately, this CD was released after the current project was completed.

CONCLUSION

The major findings of this study revealed:

1. The mean performance of the Senso C9 was significantly better than the mean performance of the Senso C8 and the subjects' own aids. The magnitude of the advantage provided by the C9 increased as the SNR became more difficult.
2. However, significant differences were not present between the C8 and the subjects' own hearing aids for any experimental condition.
3. There were no significant differences in the reported results between Site I and Site II at +7 and 0 dB SNR. However, significant differences were present between Sites I and II for the −7 dB SNR condition. Several suggestions are offered to explain why these differences occurred.
4. Significant differences in performance were not found as a function of background noise level (65 vs 75 dB SPL).
5. Performance decreased as the SNR decreased from +7 to −7 dB for all hearing aid conditions and at both sites.
6. The results for the questionnaire used in this study reported significantly greater preference for the Senso C9 in comparison to the subjects' current hearing aids after wearing the C9 for 30 days.

Acknowledgment. The authors thank Ron Meltsner at Widex Hearing Aid Company for providing a small grant to offset the direct costs involved in completing this study and allowing the subjects to purchase the hearing aids at a significantly reduced cost at the conclusion of the study. The authors also thank Francis Kuk, Ph.D. and Carl Ludvigsen of Widex Hearing Aid Company for their helpful comments on earlier drafts of this manuscript. In addition, the authors thank Tom Burroughs, Ph.D. of the Psychology Department at Washington University School of Medicine for his assistance in completing the statistical analysis and interpretation reported in this paper.

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APPENDIX A

Individual SPIN Scores for the Six Signal-to-Noise Ratios for Sites I and II for Subjects' Own Aids, Listed by Type of Signal Processing

		72/65			65/65			58/65			82/75			75/75			68/75		
Subject	*SP*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*
Site I																			
GE	Linear	5	17	22	0	0	0	0	0	0	7	23	30	3	11	14	0	0	0
FF	Linear	9	19	28	6	13	19	0	6	6	15	20	35	15	23	38	7	23	30
BD	1B HKP	18	25	43	10	24	34	4	6	10	19	25	44	14	21	35	6	20	26
NR	Linear	15	25	40	6	23	29	1	9	10	13	25	38	6	23	29	0	11	11
KB	Linear	19	23	42	10	23	33	6	14	20	16	23	39	15	22	37	2	21	23
MS	Linear	15	25	40	12	24	36	2	13	15	17	25	42	12	25	37	5	19	24
SS	1B LKP	21	25	46	19	21	40	16	23	39	22	25	47	18	25	43	14	24	38
CW	1B LKP	22	25	47	14	22	36	10	20	30	19	25	44	14	25	39	4	21	25
AH	2B LKP	20	24	44	18	21	39	2	6	8	20	25	45	10	23	33	3	5	8
JD	2B LKP	13	25	38	12	23	35	7	11	18	18	25	43	7	21	28	1	15	16
NT	2B LKP	18	25	43	13	25	38	5	18	23	18	25	43	15	23	38	7	19	26
JE	2B LKP	11	24	35	1	12	13	0	5	5	6	25	31	3	20	23	0	3	3
HK	Linear	18	25	43	6	23	29	8	10	18	23	24	47	9	21	30	3	10	13
JH	2B LKP	22	25	47	21	25	46	13	20	33	19	24	43	16	24	40	10	22	32
BA	2B LKP	13	22	35	1	12	13	0	0	0	14	24	38	4	17	21	0	0	0
AS	1B LKP	8	24	32	7	21	28	2	4	6	10	25	35	11	21	32	0	6	6
DR	2B LKP	18	25	43	15	24	39	6	16	22	14	23	37	10	22	32	6	10	16
TK	Linear	10	25	35	1	5	6	2	1	3	10	24	34	3	17	20	2	3	5
NS	1B LKP	23	25	48	21	25	46	4	20	24	21	25	46	18	25	43	13	22	35
JM	Linear	20	25	45	19	25	44	8	19	27	21	25	46	18	25	43	12	24	36
Site II																			
MB	1B PKP	17	25	42	11	25	36	2	5	7	23	25	48	10	24	34	3	5	8
HB	1B PKP	10	24	34	1	9	10	0	0	0	13	22	35	1	3	4	0	0	0
DC	2B PKP	7	22	29	0	22	22	0	0	0	14	20	34	0	23	23	0	1	1
MF	1B LKP	20	25	45	10	23	33	5	8	13	17	25	42	12	23	35	4	15	19
FH	2B LKP	18	24	42	10	22	32	0	2	2	19	25	44	11	23	34	0	0	0
SJ	2B PKP	23	25	48	15	25	40	14	24	38	23	25	48	19	25	44	10	18	28
JK	Linear	20	25	45	19	25	44	10	15	25	20	25	45	18	25	43	8	18	26
NL	1B PKP	18	25	43	16	23	39	3	5	8	21	24	45	18	24	42	8	9	17
SL	Linear	14	22	36	6	11	17	0	2	2	18	25	43	6	14	20	2	3	5
TL	2B PKP	18	25	43	5	9	14	2	5	7	17	20	37	8	14	22	3	6	9
AM	1B PKP/2B LKP	10	21	31	0	3	3	0	0	0	11	20	31	0	5	5	0	0	0
JS	1B LKP	20	24	44	11	23	34	5	7	12	19	24	43	14	22	36	7	12	19
LS	1B HKP	11	22	33	4	15	19	0	1	1	17	21	38	6	11	17	0	0	0
MS	Linear	9	21	30	0	5	5	0	0	0	12	21	33	1	9	10	0	0	0
MY	2B PKP	10	22	32	4	14	18	0	0	0	16	21	37	5	12	17	0	0	0
JW	1B LKP	21	25	46	13	24	37	6	18	24	21	25	46	15	24	39	5	15	20
GS	1B LKP	17	25	42	6	19	25	0	2	2	21	25	46	11	24	35	4	7	11
MA	2B LKP	19	21	40	9	19	28	0	1	1	23	25	48	12	17	29	2	2	4
WN	2B PKP	11	22	33	9	18	27	0	3	3	12	25	37	5	11	16	2	0	2
EL	Linear	12	23	35	7	20	27	0	0	0	22	24	46	12	24	36	2	3	5

LP = low predictability, HP = high predictability, T = total, SP = signal processing.

1B LKP = one band low kneepoint; 2B LKP = two band low kneepoint; 1B HKP = one band high kneepoint; 1B PKP = one band programmable kneepoint; 2B PKP = two band programmable kneepoint.

APPENDIX B

Individual SPIN Scores for the Six Signal-to-Noise Ratios for Sites I and II for Senso C8, Listed by Type of Signal Processing

		72/65			65/65			58/65			82/75			75/75			68/75		
Subject	*SP*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*
Site I																			
GE	Linear	11	24	35	10	20	30	0	0	0	9	24	33	4	15	19	0	0	0
FF	Linear	14	24	38	3	11	14	6	7	13	10	19	29	11	20	31	6	15	21
BD	1B HKP	17	25	42	12	22	34	8	14	22	14	24	38	5	15	20	11	13	24
NR	Linear	15	23	38	8	24	32	0	7	7	17	25	42	11	24	35	3	17	20
KB	Linear	18	25	43	13	23	36	7	22	29	19	25	44	21	24	45	11	21	32
MS	Linear	17	25	42	10	24	34	0	10	10	15	25	40	15	24	39	1	14	15
SS	1B LKP	22	25	47	17	24	41	13	23	36	22	25	47	18	25	43	16	23	39
CW	1B LKP	17	25	42	9	20	29	3	8	11	20	25	45	11	23	34	6	17	23
AH	2B LKP	20	25	45	14	24	38	8	19	27	18	24	42	9	25	34	5	16	21
JD	2B LKP	13	25	38	9	20	29	8	14	22	17	25	42	11	16	27	2	15	17
NT	2B LKP	21	25	46	14	24	38	8	15	23	18	24	42	14	25	39	11	22	33
JE	2B LKP	18	25	43	10	25	35	3	11	14	17	24	41	16	24	40	1	15	16
HK	Linear	19	23	42	4	18	22	1	7	8	12	23	35	3	22	25	0	11	11
JH	2B LKP	22	25	47	20	25	45	7	20	27	24	25	49	25	24	49	16	21	37
BA	2B LKP	17	25	42	8	20	28	5	5	10	16	25	41	3	4	7	8	20	28
AS	1B LKP	16	25	41	14	24	38	7	10	17	16	24	40	12	21	33	2	9	11
DR	2B LKP	18	25	43	19	25	44	7	20	27	16	24	40	17	24	41	8	15	23
TK	Linear	15	25	40	8	16	24	1	2	3	17	24	41	1	12	13	0	1	1
NS	1B LKP	21	25	46	13	25	38	11	20	31	21	25	46	19	25	44	10	23	33
JM	Linear	22	25	47	19	25	44	11	23	34	21	25	46	20	25	45	10	23	33
Site II																			
MB	1B PKP	13	25	38	6	12	18	2	6	8	23	24	47	9	19	28	3	7	10
HB	1B PKP	15	25	40	2	10	12	0	0	0	14	25	39	5	13	18	0	0	0
DC	2B PKP	10	23	33	7	8	15	0	5	5	19	24	43	9	24	33	0	4	4
MF	1B LKP	17	24	41	8	23	31	4	8	12	17	25	42	9	19	28	4	8	12
FH	2B LKP	19	23	42	13	23	36	5	6	11	21	25	46	14	22	36	6	7	13
SJ	2B PKP	22	25	47	13	25	38	5	13	18	22	25	47	12	23	35	5	15	20
JK	Linear	21	25	46	17	25	42	4	13	17	23	25	48	18	25	43	8	17	25
NL	1B PKP	21	23	44	8	21	29	5	12	17	25	24	49	20	25	45	3	16	19
SL	Linear	17	25	42	7	18	25	4	9	13	19	24	43	9	16	25	3	4	7
TL	2B PKP	9	24	33	6	12	18	2	6	8	23	25	48	9	14	23	3	7	10
AM	1B PKP/2B LKP	6	23	29	7	19	26	1	3	4	13	24	37	1	17	18	0	3	3
JS	1B LKP	18	23	41	14	23	37	4	9	13	19	24	43	14	22	36	5	10	15
LS	1B HKP	13	24	37	3	14	17	0	0	0	14	25	39	11	20	31	0	0	0
MS	Linear	12	24	36	4	16	20	0	0	0	13	23	36	5	14	19	0	0	0
MY	2B PKP	11	23	34	5	13	18	0	0	0	16	25	41	7	14	21	1	1	2
JW	1B LKP	19	25	44	12	24	36	6	14	20	17	25	42	17	24	41	2	13	15
GS	1B LKP	18	25	43	11	16	27	0	0	0	15	25	40	9	16	25	3	7	10
MA	2B LKP	22	25	47	4	17	21	0	0	0	24	23	47	15	21	36	8	7	15
WN	2B PKP	15	23	38	7	23	30	1	7	8	17	22	39	12	22	34	3	5	8
EL	Linear	13	20	33	6	13	19	0	0	0	15	23	38	5	13	18	4	2	6

LP = low predictability, HP = high predictability, T = total, SP = signal processing.

1B LKP = one band low kneepoint; 2B LKP = two band low kneepoint; 1B HKP = one band high kneepoint; 1B PKP = one band programmable kneepoint; 2B PKP = two band programmable kneepoint.

APPENDIX C

Individual SPIN Scores for the Six Signal-to-Noise Ratios for Sites I and II and Senso C9, Listed by Type of Signal Processing

		72/65			65/65			58/65			82/75			75/75			68/75		
Subject	*SP*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*	*LP*	*HP*	*T*
Site I																			
GE	Linear	16	24	40	14	25	39	5	20	25	16	24	40	16	25	41	12	24	36
FF	Linear	21	25	46	16	24	40	5	18	23	21	25	46	19	21	40	13	25	38
BD	1B HKP	20	25	45	16	25	41	11	22	33	23	25	48	18	25	43	14	24	38
NR	Linear	22	25	47	16	25	41	11	25	36	20	25	45	19	25	44	15	25	40
KB	Linear	24	25	49	15	25	40	11	22	33	18	25	43	15	25	40	14	24	38
MS	Linear	20	25	45	18	25	43	14	24	38	21	25	46	18	24	42	8	25	33
SS	1B LKP	21	25	46	21	25	46	20	25	45	24	25	49	23	24	47	18	25	43
CW	1B LKP	24	25	49	20	25	45	15	25	40	21	25	46	18	24	42	14	25	39
AH	2B LKP	25	25	50	16	25	41	13	25	38	23	25	48	17	25	42	16	25	41
JD	2B LKP	16	25	41	19	25	44	13	22	35	20	25	45	16	24	40	16	24	40
NT	2B LKP	20	23	43	21	24	45	15	23	38	19	25	44	17	25	42	21	25	46
JE	2B LKP	18	25	43	16	24	40	9	24	33	20	25	45	16	25	41	11	24	35
HK	Linear	18	25	43	15	24	39	11	24	35	15	25	40	14	25	39	14	24	38
JH	2B LKP	24	25	49	23	25	48	22	24	46	25	25	50	19	25	44	23	25	48
BA	2B LKP	19	25	44	17	25	42	9	21	30	19	25	44	15	25	40	14	24	38
AS	1B LKP	19	25	44	12	24	36	12	23	35	19	24	43	17	24	41	9	18	27
DR	2B LKP	21	25	46	20	25	45	16	25	41	20	25	45	20	24	44	10	24	34
TK	Linear	19	24	43	15	24	39	9	20	29	18	25	43	14	23	37	11	20	31
NS	1B LKP	24	25	49	22	25	47	17	25	42	19	25	44	21	25	46	20	25	45
JM	Linear	21	25	46	23	25	48	19	25	44	22	25	47	23	25	48	20	24	44
Site II																			
MB	1B PKP	23	25	48	8	15	23	23	24	47	23	24	47	17	24	41	7	15	22
HB	1B PKP	19	25	44	14	24	38	6	16	22	15	25	40	15	24	39	0	9	9
DC	2B PKP	16	22	38	5	21	26	7	7	14	15	25	40	5	23	28	0	7	7
MF	1B LKP	21	25	46	13	24	37	9	21	30	20	25	45	16	25	41	10	18	28
FH	2B LKP	23	25	48	16	24	40	7	11	18	21	25	46	20	24	44	4	13	17
SJ	2B PKP	25	25	50	22	25	47	17	25	42	25	25	50	25	25	50	15	25	40
JK	Linear	23	25	48	21	25	46	11	22	33	20	25	45	18	25	43	14	22	36
NL	1B PKP	21	25	46	16	25	41	7	17	24	23	25	48	20	25	45	15	20	35
SL	Linear	21	24	45	15	23	38	5	16	21	19	25	44	17	23	40	8	16	24
TL	2B PKP	24	25	49	20	25	45	11	18	29	24	25	49	24	25	49	7	18	25
AM	1B PKP/2B LKP	19	25	44	11	23	34	8	18	26	20	25	45	14	25	39	7	18	25
JS	1B LKP	24	25	49	17	23	40	10	21	31	21	25	46	21	24	45	10	22	32
LS	1B HKP	17	24	41	6	25	31	9	16	25	17	25	42	17	22	39	3	15	18
MS	Linear	16	25	41	9	18	27	3	6	9	17	25	42	10	25	35	5	5	10
MY	2B PKP	21	24	45	15	23	38	8	18	26	21	24	45	15	24	39	12	18	30
JW	1B LKP	21	25	46	17	25	42	20	23	43	24	25	49	14	24	38	5	17	22
GS	1B LKP	18	25	43	16	25	41	2	13	15	18	25	43	11	24	35	4	15	19
MA	2B LKP	20	25	45	16	24	40	14	16	30	23	25	48	18	24	42	7	21	28
WN	2B PKP	20	25	45	16	25	41	12	21	33	20	25	45	17	24	41	9	17	26
EL	Linear	16	24	40	13	24	37	4	16	20	19	24	43	18	22	40	6	10	16

LP = low predictability, HP = high predictability, T = total, SP = signal processing.

1B LKP = one band low kneepoint; 2B LKP = two band low kneepoint; 1B HKP = one band high kneepoint; 1B PKP = one band programmable kneepoint; 2B PKP = two band programmable kneepoint.